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2204.03796
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Electroweak Fits and Higgs Physics

武 雷

1. Post-Higgs Era

July 4, 2022
CERN

QUANTUM PHYSICS | OPINION

10 Years after the Higgs, Physicists Are Optimistic for More Discoveries

The Large Hadron Collider recently reopened after upgrades and is ready to explore new territory

By Marcela Carena on July 5, 2022

nature

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Article | Open Access |

A detailed m by the ATLAS discovery

The ATLAS Collaboration

nature

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Article | Open Access | Published: 04 July 2022

A port experi

The CMS Coll

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Perspective | Published: 04 July 2022

The Higgs boson turns ten

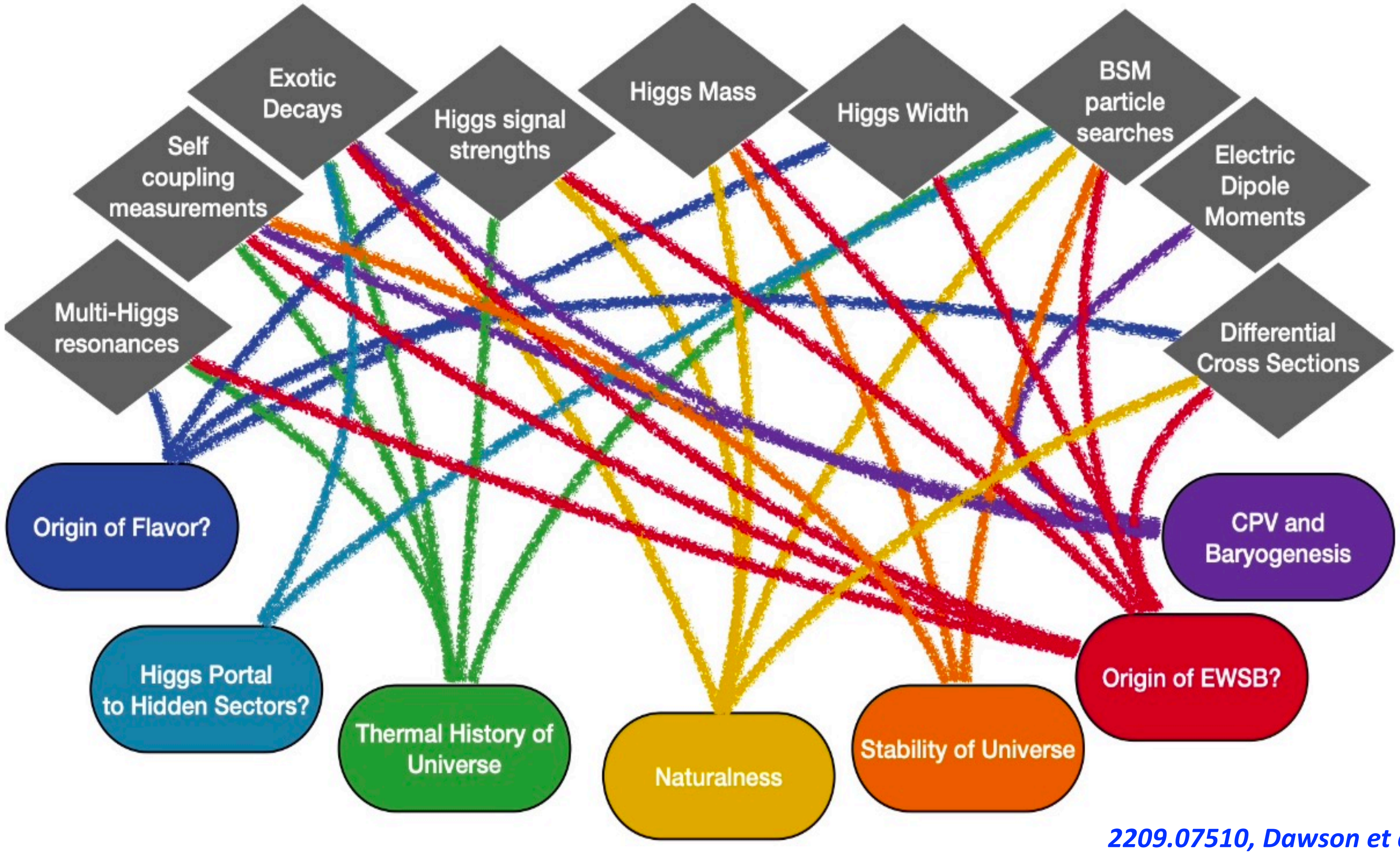
Gavin P. Salam, Lian-Tao Wang & Giulia Zanderighi

Nature **607**, 41–47 (2022) | Cite this article

29k Accesses | **3** Citations | **349** Altmetric | Metrics

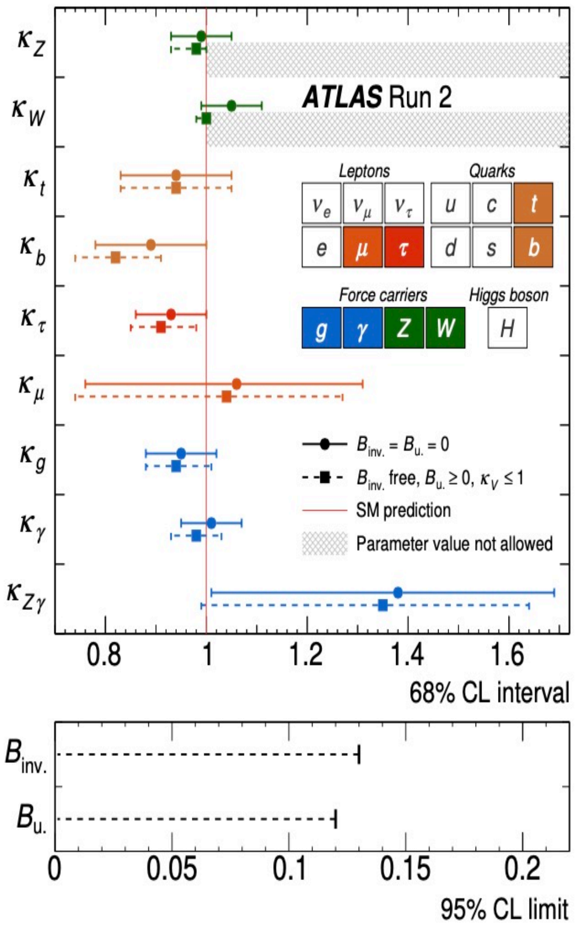
1. Post-Higgs Era

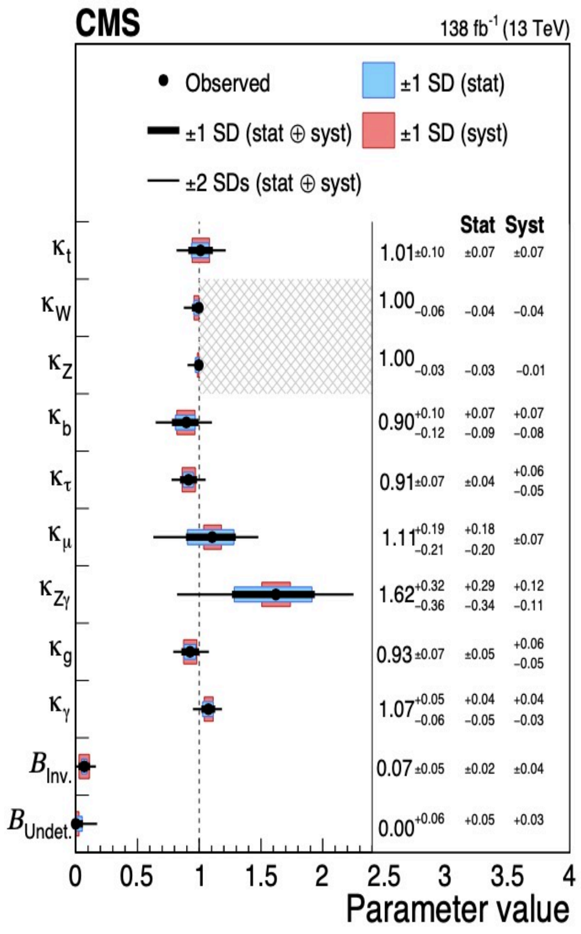
Post-Higgs Era: Precision Measurements and New Physics



2209.07510, Dawson et al.

1. Post-Higgs Era





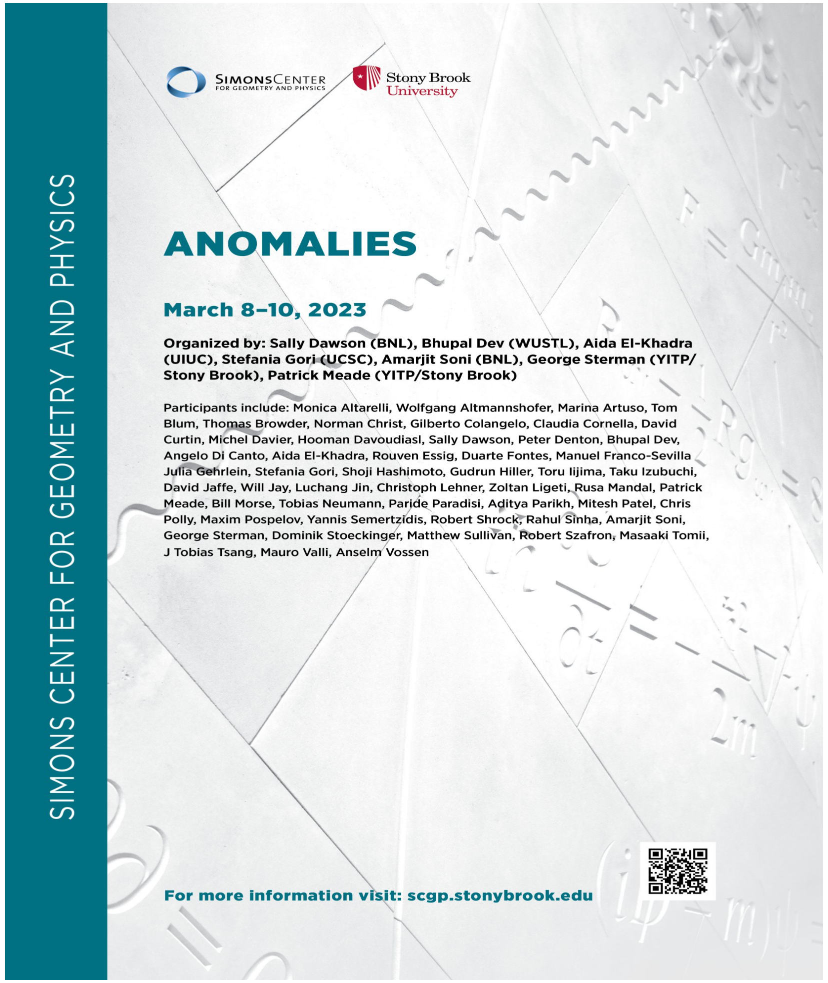
M_h=125 GeV

1902.00134, Cepeda

Process	σ(pb)@14 TeV
ggF (N^{3}LO QCD + NLO EW)	$54.72^{+4.28\%(\text{theory})+1.85\%(\text{PDF})+2.60\%(\alpha_s)}_{-6.46\%(\text{theory})-1.85\%(\text{PDF})+2.62\%(\alpha_s)}$
VBF (NNLO QCD)	$4.260^{+.45\%(\text{scale})+2.1\%(\text{PDF}+\alpha_s)}_{-.34\%(\text{scale})-2.1\%(\text{PDF}+\alpha_s)}$
Wh (NNLO QCD+NLO EW)	$1.498 \pm .51\%(\text{scale}) \pm 1.35\%(\text{PDF}+\alpha_s)$
Zh (NNLO QCD+NLO EW)	$.981^{+3.61\%(\text{scale})+1.90\%(\text{PDF}+\alpha_s)}_{-2.94\%(\text{scale})-1.90\%(\text{PDF}+\alpha_s)}$
$t\bar{t}h$ (NLO QCD + NLO EW)	$.6128^{+6.0\%(\text{scale})+3.5\%(\text{PDF}+\alpha_s)}_{-9.2\%(\text{scale})-3.5\%(\text{PDF}+\alpha_s)}$

Decay	Branching Ratio
$h \to b\bar{b}$	$.582^{+.65\%(\text{Theory})+.72\%(m_q)+.78\%(\alpha_s)}_{-.65\%(\text{Theory})-.74\%(m_q)-.80\%(\alpha_s)}$
$h \to c\bar{c}$	$.02891^{+1.20\%(\text{Theory})+5.26\%(m_q)+1.25\%(\alpha_s)}_{-1.20\%(\text{Theory})-.98\%(m_q)-1.25\%(\alpha_s)}$
$h \to \tau^+\overline{\tau}^-$	$.06272^{+1.17\%(\text{Theory})+.98\%(m_q)+.62\%(\alpha_s)}_{-1.16\%(\text{Theory})-.99\%(m_q)-.62\%(\alpha_s)}$
$h \to \gamma\gamma$	$.00227^{+1.73\%(\text{Theory})+.93\%(m_q)+.61\%(\alpha_s)}_{-1.72\%(\text{Theory})-.99\%(m_q)-.62\%(\alpha_s)}$
$h \to ZZ \to 4l(l = e, \mu, \tau)$	$.0002745 \pm 2.18\%$
$h \to WW \to l^+l^-\nu\overline{\nu}(l = e, \mu, \tau)$	$.02338 \pm 2.18\%$

1. Post-Higgs Era



Light Higgs Boson?

New Resonance?

B anomalies?

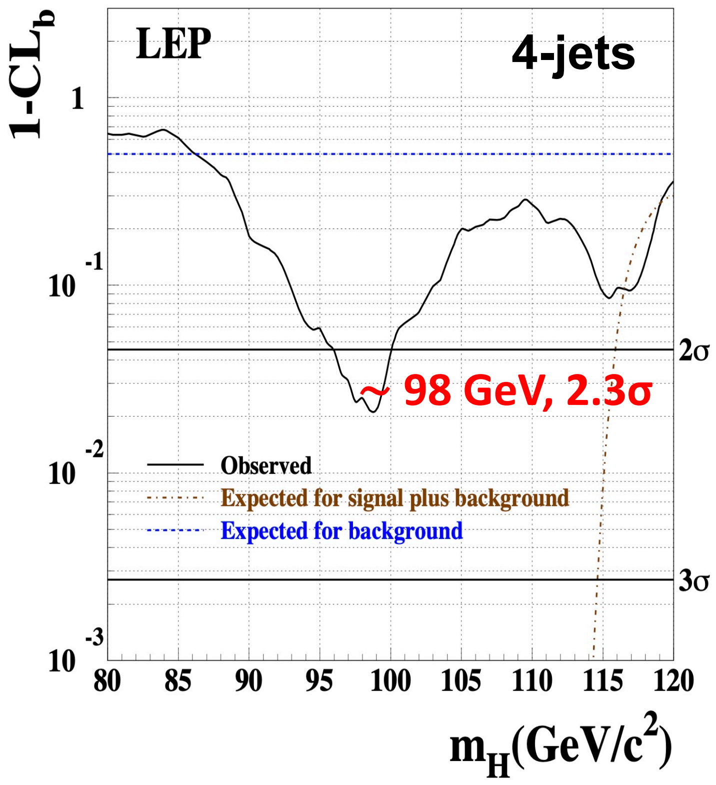
Muon g-2?

CDF-II W mass?

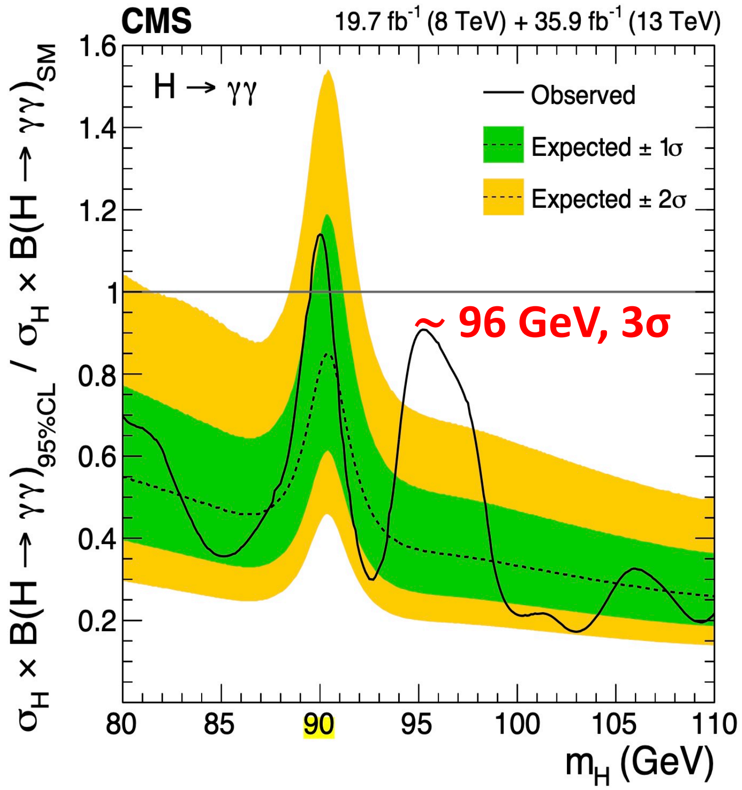
1. Post-Higgs Era

"Light Higgs boson? "

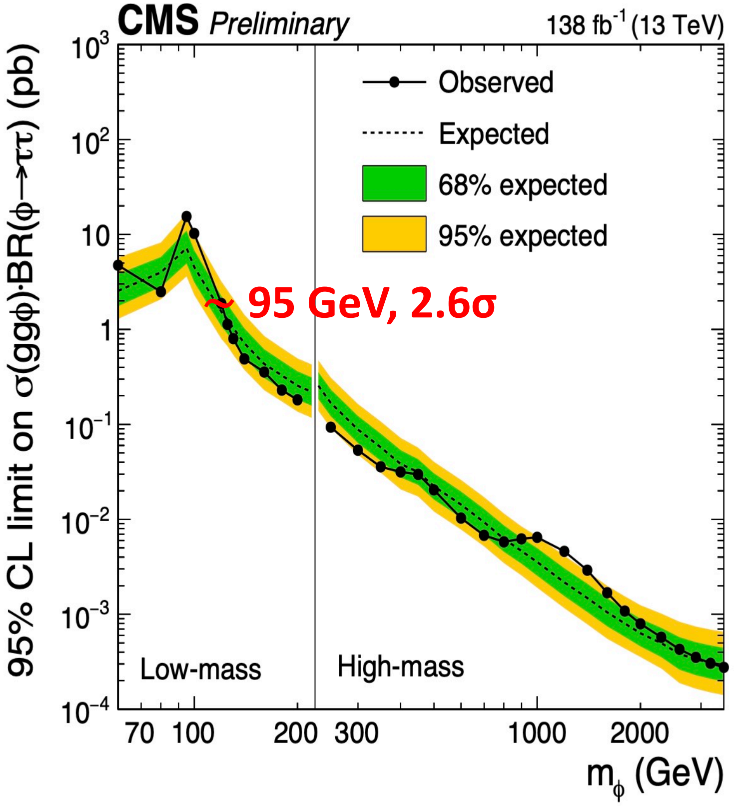
0306033



1811.08459, Sirunyan



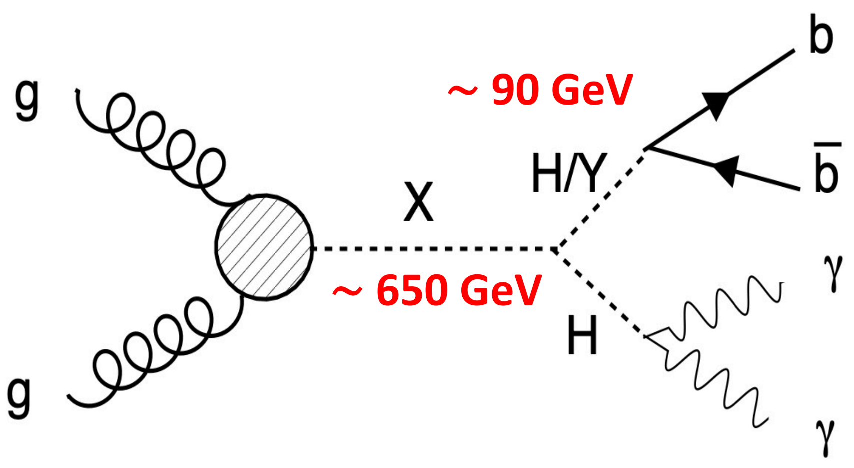
CMS PAS HIG-21-001

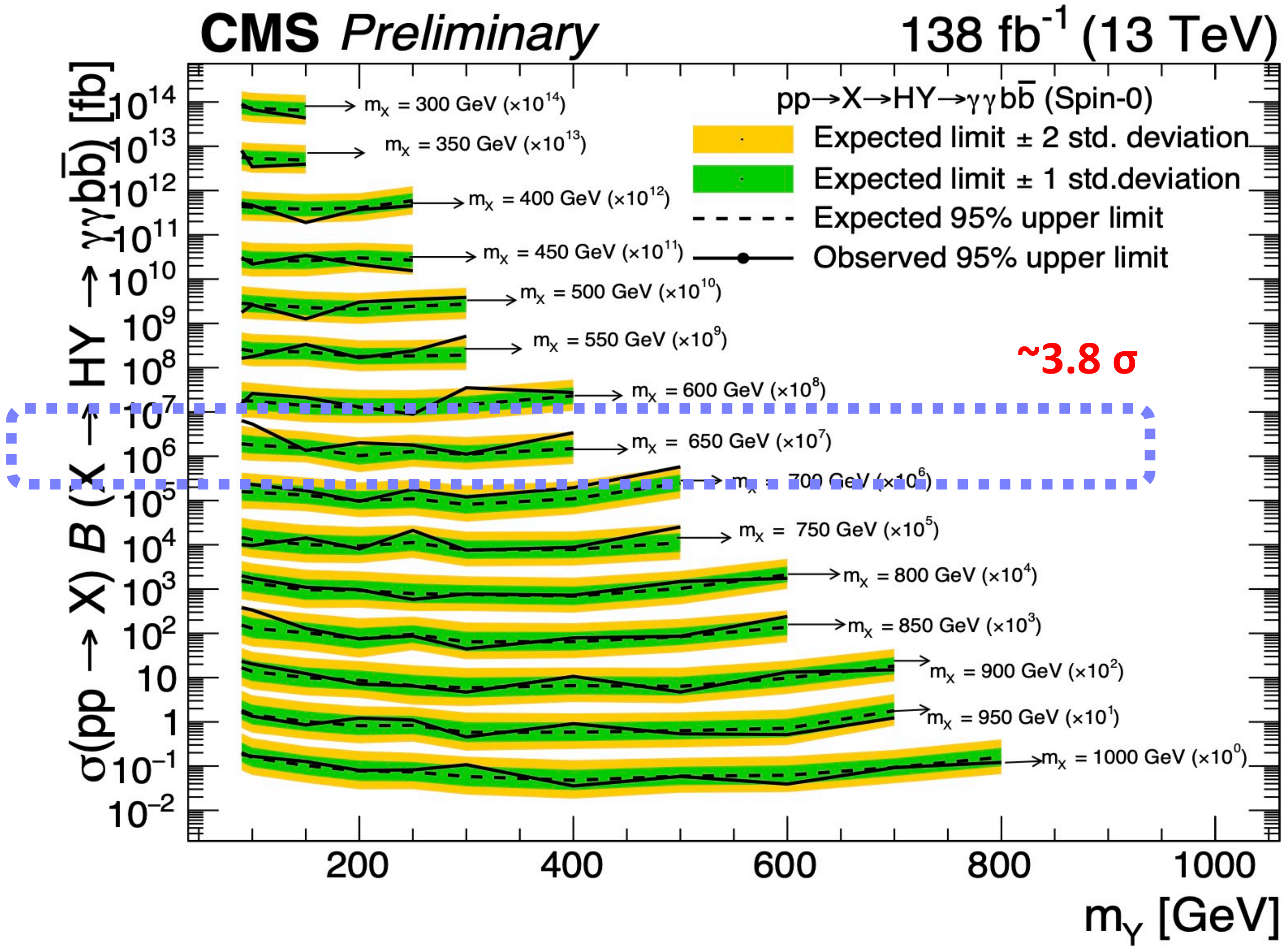


1. Post-Higgs Era

“ A new resonance? ”

CMS-PAS-HIG-21-011





1. Post-Higgs Era

“ A new resonance? ”

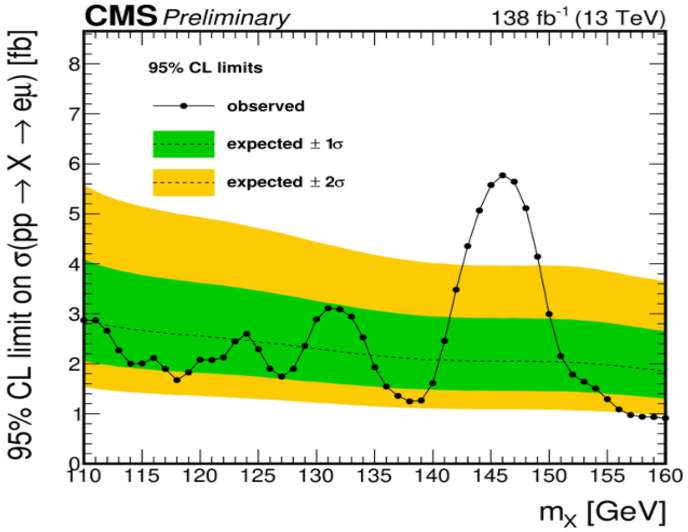
CMS

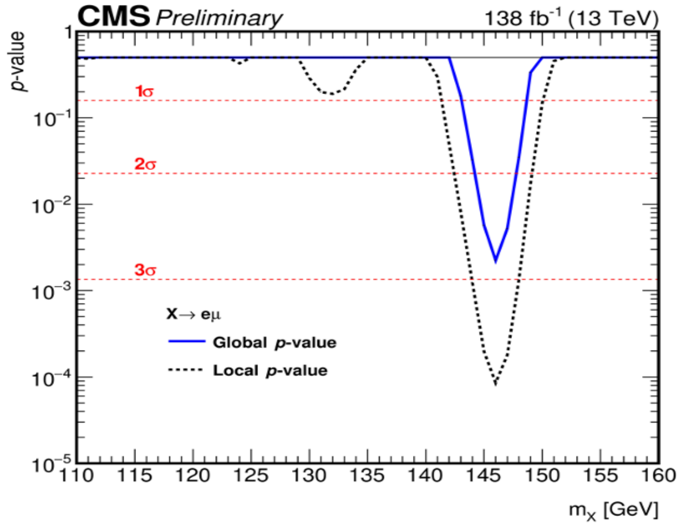
LFV SM (H_{125}) or SM-like Exotic $X \rightarrow e\mu$ (110 GeV<m_H<160 GeV)

New!

CMS-PAS-HIG-22-002

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-22-002/index.html





- Observed & expected 95% CL UL on σ ($pp \rightarrow X \rightarrow e\mu$)

- Excess observed for $m_{e\mu}$~146 GeV with global (2.8 σ) and local (3.8σ) significances
- Not visible in ATLAS $m_{e\mu}$ spectrum (PLB 801 (2019) 135148), more data needed to conclude!

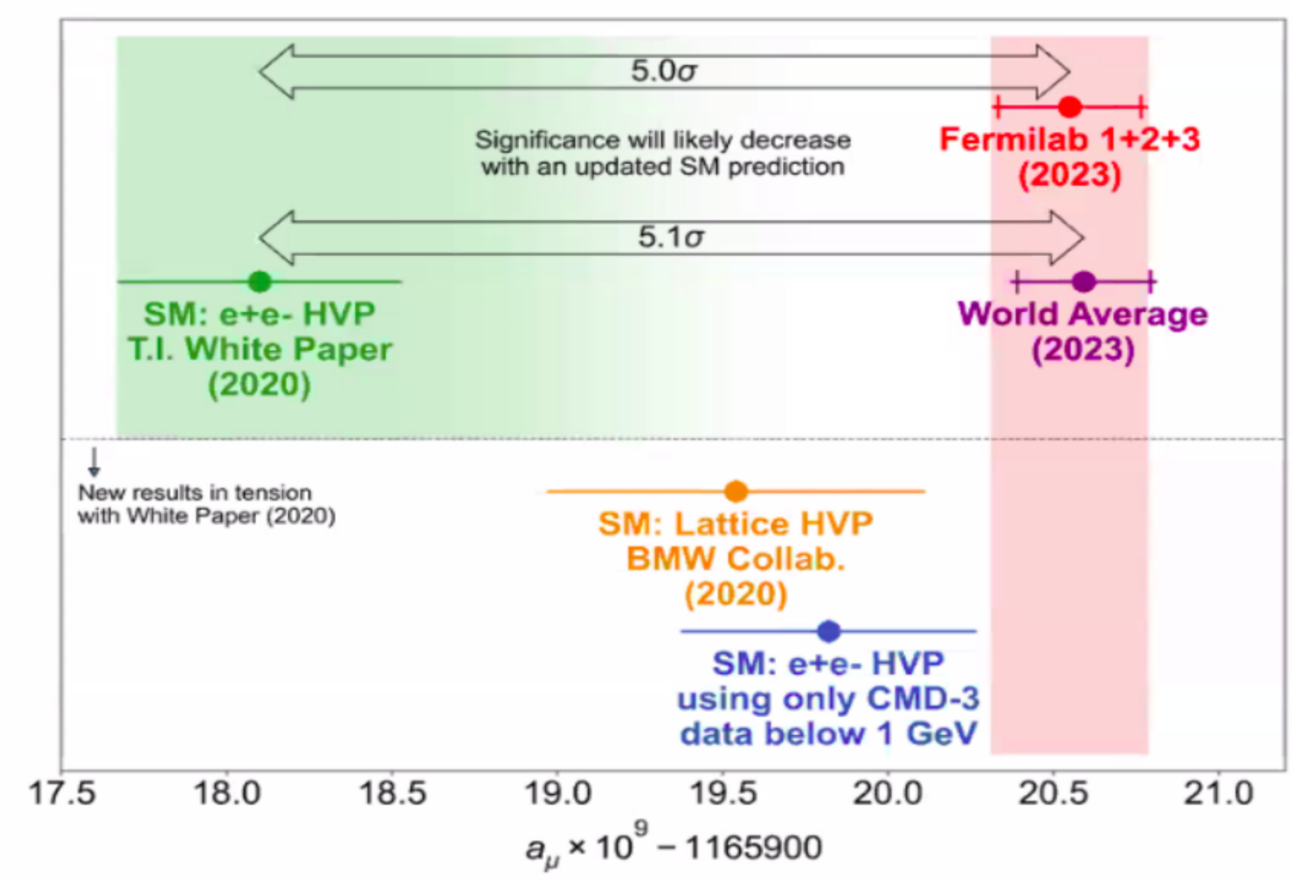
S. Gascon-Shotkin Rencontres de Moriond EW 2023, La Thuile, IT Mar 23 2023 13

1. Post-Higgs Era

“ Muon g-2? ”

10th of August, 2023

https://muon-g-2.fnal.gov/



1. Post-Higgs Era

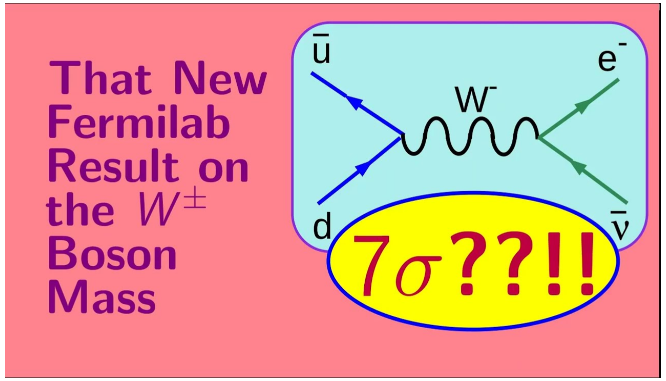
" *Overweight W mass？* "

Science, 2022, CDF-II

$$m_W^{\mathrm{CDF}} = 80.4335 \pm 0.0094\ \mathrm{GeV}$$

$$m_W^{\mathrm{SM}} = 80.357 \pm 0.006\ \mathrm{GeV}$$

April 8, 2022



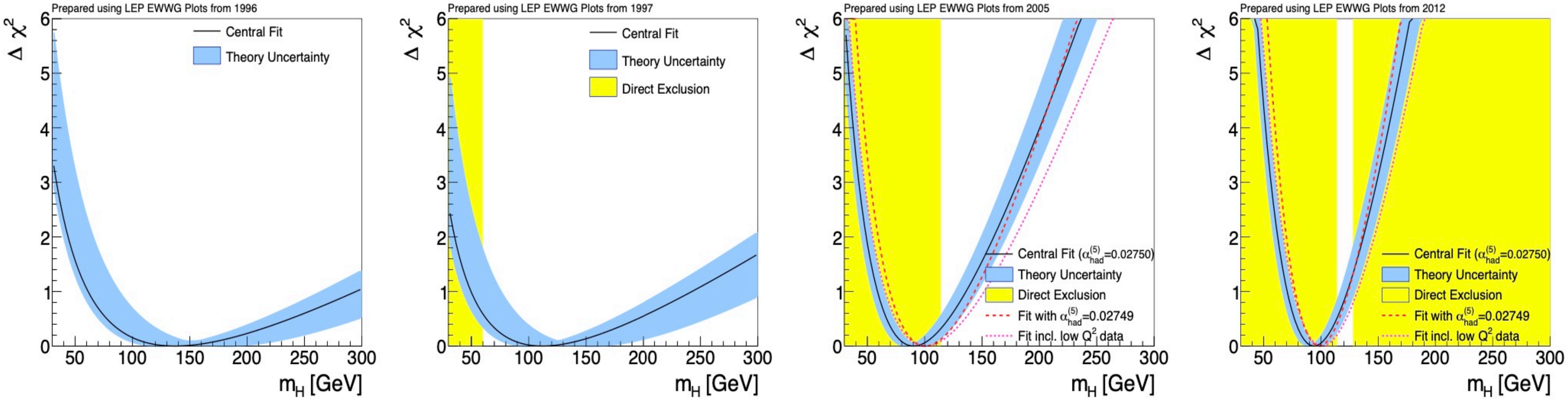
W boson turns 40

Forty years ago today, physicists at CERN announced to the world that they had discovered the electrically charged carrier of the weak force, one of nature's four fundamental forces

25 JANUARY, 2023 | By Ana Lopes

0509008

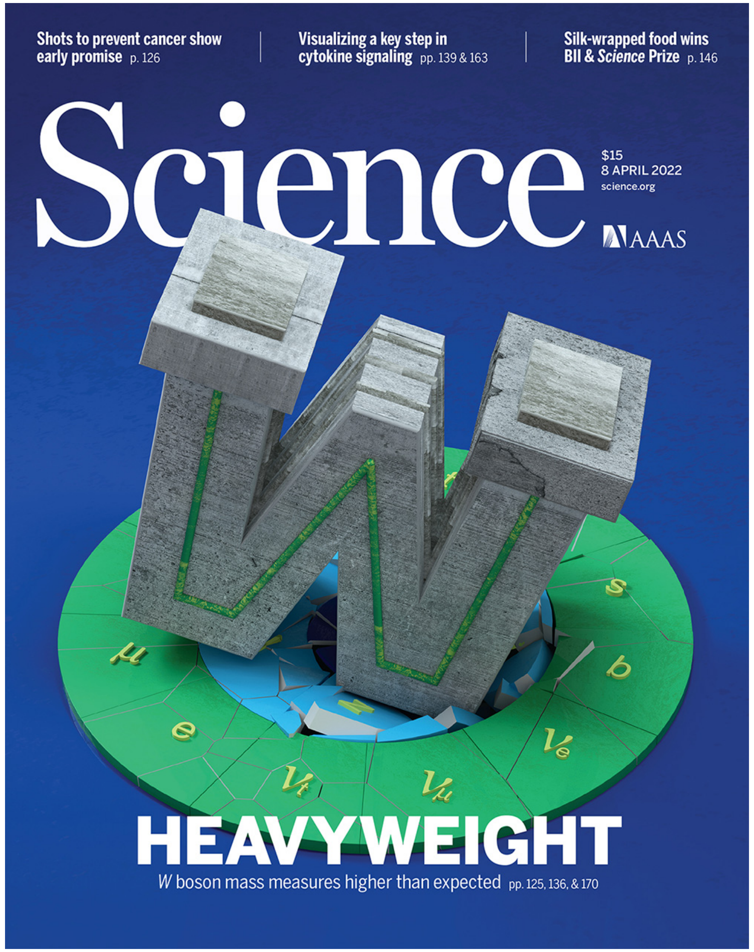
'blue-band' plots



2. EW Precision Fits and NP Hints

2204.03796, Lu, Wu, Wu, Zhu

2204.03996, Athron, Fowlie, Lu, Wu, Wu, Zhu



Three important questions:

Internal Consistency of the SM ?

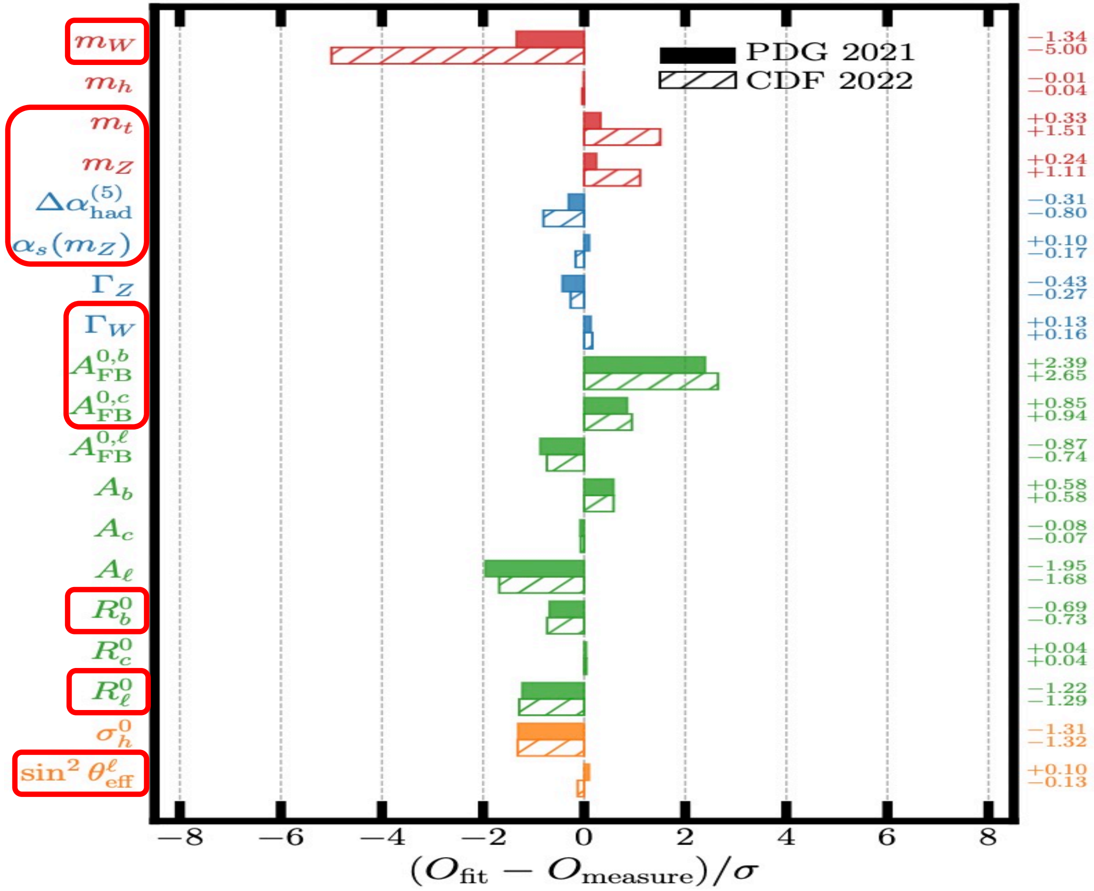
New Physics Scale ?

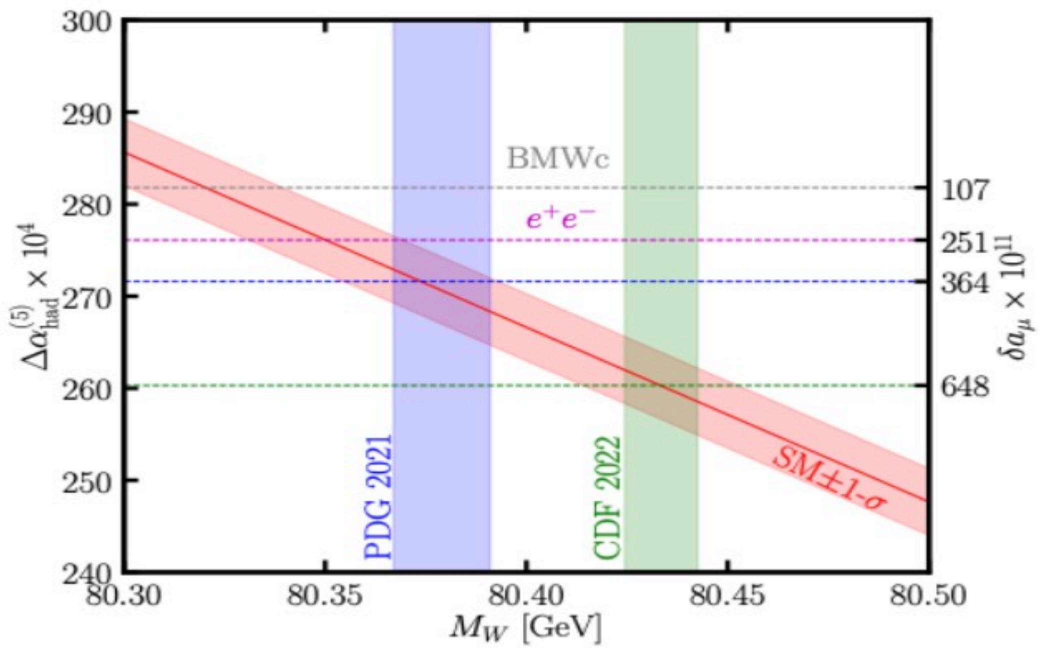
Possible New Physics Models ?

2. EW Precision Fits and NP Hints

Internal Consistency of the SM :

M_W correlates
- **positively** with m_t and M_Z
- **negatively** with $\alpha(M_Z)$ and $\alpha_s(M_Z)$

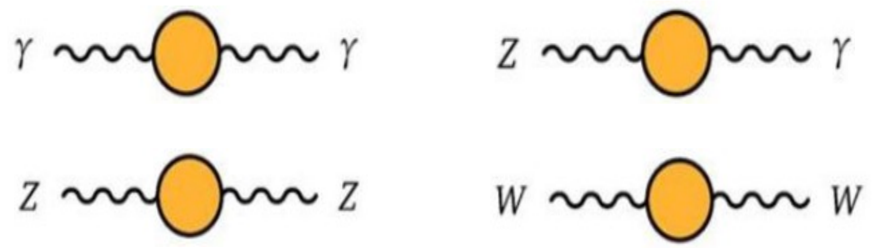




2. EW Precision Fits and NP Hints

Oblique Parameters:

$$(M_W^2)_{\rm phys} = (M_W^{SM})^2\left[1 - \frac{\alpha S}{2(c_w^2 - s_w^2)} + \frac{c_w^2\,\alpha T}{c_w^2 - s_w^2} + \frac{\alpha U}{4 s_w^2}\right]$$



$$\begin{aligned}
\alpha S &= 4 s_W^2 c_W^2\left[\Pi_{ZZ}(0) - (c_W^2 - s_W^2)/(s_W c_W)\cdot \Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right] \\
\alpha T &= \Pi_{WW}(0)/M_W^2 - \Pi_{ZZ}(0)/M_Z^2 \\
\alpha U &= 4 s_W^2\left[\Pi'_{WW}(0) - c_W^2\Pi'_{ZZ}(0) - 2 s_W c_W \Pi'_{Z\gamma}(0) - s_W^2\Pi'_{\gamma\gamma}(0)\right]
\end{aligned}$$

PRD 46 (1992) 381-409, Peskin and Takeuchi

(1): The electroweak gauge group must be $SU_L(2)\times U_Y(1)$, with no new electroweal gauge bosons apart from the photon, the $W^\pm$ and the Z.

(2): The couplings of the new physics to light fermions are suppressed compared to it couplings to the gauge bosons.

(3): The intrinsic scale, M, of the new physics is large in comparison with M_w and M_Z

- **Exception-1: NP is comparatively light.**
- **Exception-2: NP is comparatively large, but the low-energy measurements become sufficiently accurate.**

9306267, Maksymyk, Burgess, London

2. EW Precision Fits and NP Hints

S, T and U:

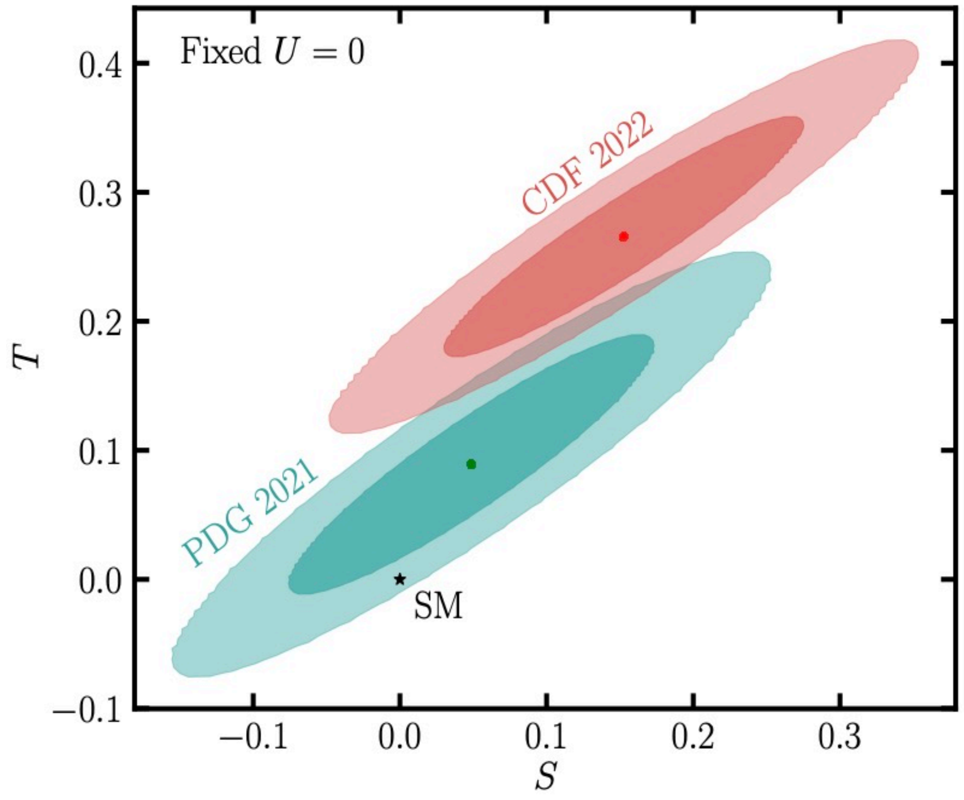
$U=0$, 14 dof	PDG 2021 Result	PDG 2021 Correlation S	PDG 2021 Correlation T	CDF 2022 Result	CDF 2022 Correlation S	CDF 2022 Correlation T
	$\chi^2_{\text{min}} = 15.48$	S	T	$\chi^2_{\text{min}} = 17.82$	S	T
S	0.05 ± 0.08	1.00	0.92	0.15 ± 0.08	1.00	0.93
T	0.09 ± 0.07		1.00	0.27 ± 0.06		1.00

favor positive

13 dof	PDG 2021 Result	PDG 2021 Correlation S	PDG 2021 Correlation T	PDG 2021 Correlation U	CDF 2022 Result	CDF 2022 Correlation S	CDF 2022 Correlation T	CDF 2022 Correlation U
	$\chi^2_{\text{min}} = 15.42$	S	T	U	$\chi^2_{\text{min}} = 15.44$	S	T	U
S	0.06 ± 0.10	1.00	0.90	-0.57	0.06 ± 0.10	1.00	0.90	-0.59
T	0.11 ± 0.12		1.00	-0.82	0.11 ± 0.12		1.00	-0.85
U	-0.02 ± 0.09			1.00	0.14 ± 0.09			1.00

due to W width in fits

2204.03796, Lu, Wu, Wu, Zhu



2. EW Precision Fits and NP Hints

New Physics scale:

$$|H^\dagger D_\mu H|^2/\Lambda^2 \quad\quad H^\dagger W^{\mu\nu} B_{\mu\nu} H/\Lambda^2 \quad\quad \left(H^\dagger W^{\mu\nu} H\right)\left(H^\dagger W_{\mu\nu} H\right)/\Lambda^4$$

$\downarrow$ **T parameter** $\quad\downarrow$ **S parameter** $\quad\downarrow$ **U parameter**

$\mathcal{O}(0.1) \xrightarrow{\text{pert. couplings}}$ **Λ ~ 10 TeV**

$\mathcal{O}(0.1) \xrightarrow{\text{pert. couplings}}$ **Λ ~ 0.1 TeV**

2. EW Precision Fits and NP Hints

Possible NP models:

How to make T larger: $\alpha T = \rho$

$$\rho = \frac{M_W^2}{c_W^2 M_Z^2}$$

= 1

(tree level)

NP @ tree-level

$$\rho = \frac{\sum_i \left[I_i(I_i+1) - (I_i^3)^2\right] v_i^2}{2\sum_i (I_i^3)^2 v_i^2}$$

(higher Higgs representations: Triplet etc)

NP @ loop-level

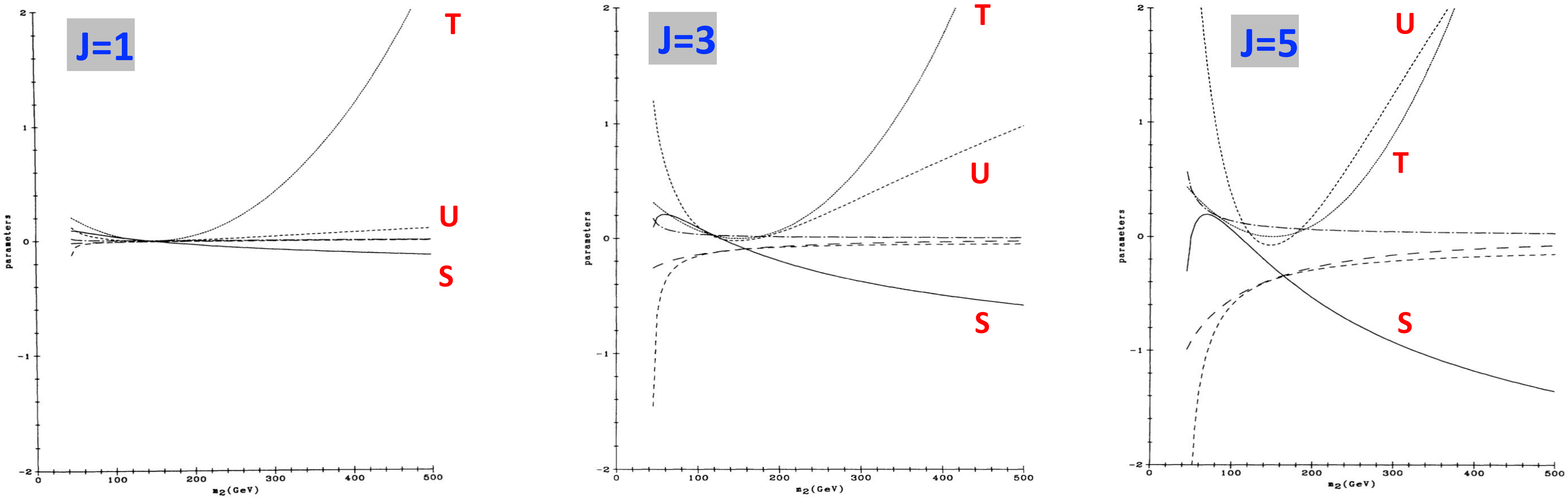
$$\rho = 1 + \frac{3g^2}{64\pi^2}\frac{m_t^2 - m_b^2}{M_W^2} - \frac{11}{192\pi^2} g'^2 \log\frac{M_h^2}{M_Z^2} + \cdots$$

(new particles: 2HDM etc)

2. EW Precision Fits and NP Hints

How to make S and U larger:

PRD 49 (1994) 1409-1416, Lavoura and Li e.g. multiplet scalars high isospin, light states



3. Inert 2HDM

2204.03693, Fan, Tang, Sming, Wu

i2HDM:

Discrete Z_2 symmetry ($H_1 \to H_1$ and $H_2 \to -H_2$)

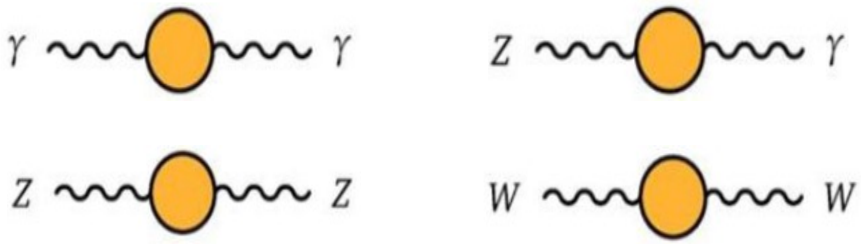
$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + iG^0\right) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S + iA) \end{pmatrix}$$

$$V = \mu_1^2|H_1|^2 + \lambda_1|H_1|^4 + \mu_2^2|H_2|^2 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left\{(H_1^\dagger H_2)^2 + h.c.\right\}$$

PRD 18 (1978) 2574, Deshpande, Ma

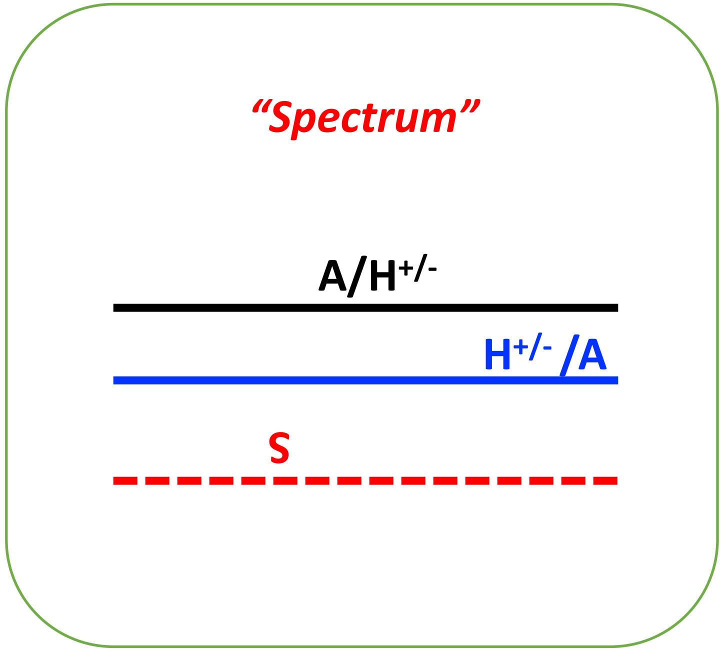
3. Inert 2HDM

Oblique Parameter



$$
\begin{cases}
S = \dfrac{1}{2\pi}\left[\dfrac{1}{6}\log\left(\dfrac{m_S^2}{m_{H^\pm}^2}\right) - \dfrac{5}{36} + \dfrac{m_S^2 m_A^2}{3(m_A^2 - m_S^2)^2} + \dfrac{m_A^4(m_A^2 - 3m_S^2)}{6(m_A^2 - m_S^2)^3}\log\left(\dfrac{m_A^2}{m_S^2}\right)\right] \\[2em]
T = \dfrac{1}{32\pi^2\alpha v^2}\left[F(m_{H^\pm}^2, m_A^2) + F(m_{H^\pm}^2, m_S^2) - F(m_A^2, m_S^2)\right]
\end{cases}
$$

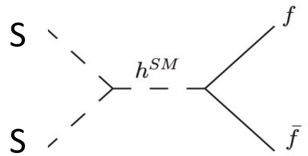
$$
= 32 i\pi^2 \int \frac{d^4k}{(2\pi)^4}\, k^2 \frac{(m_+^2 - m_1^2)(m_+^2 - m_2^2)}{(k^2 - m_+^2)^2(k^2 - m_1^2)(k^2 - m_2^2)}
$$



3. Inert 2HDM

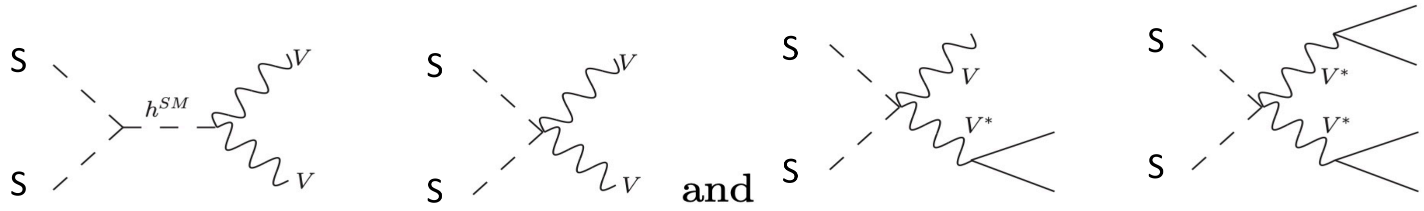
Relic Density of DM

- annihilation through Higgs into fermions



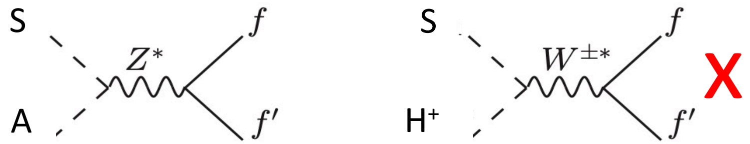
depends on g_{DMh} coupling; dominant channel for $M_{DM} < M_h/2$

- annihilation into gauge bosons (also into virtual states)



crucial for heavy masses; non-negligible for $M_h/2 < M_{DM} < M_W$

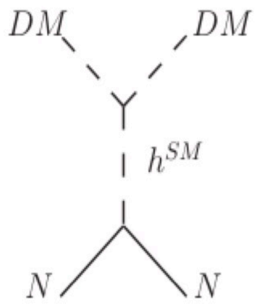
- coannihilation



very important when particles have similar masses

3. Inert 2HDM

Direct Detection

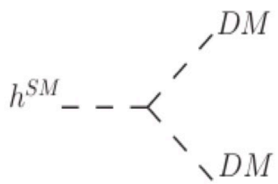


σ_{DM-N}

DM-scattering on nucleus through the Higgs exchange

$$\sigma_{DM-N} \propto g^2_{DMh}/(M_{H_1} + M_N)^2$$

Higgs invisible decay



$\Gamma^{inv}_{h^{SM}}$

Higgs invisible decays for $M_{DM} < M_h/2$

$$\Gamma(h \to H_1 H_1) = \frac{g^2_{DMh} v^2}{32\pi M_h} \sqrt{1 - \frac{4M^2_{H_1}}{M^2_h}}$$

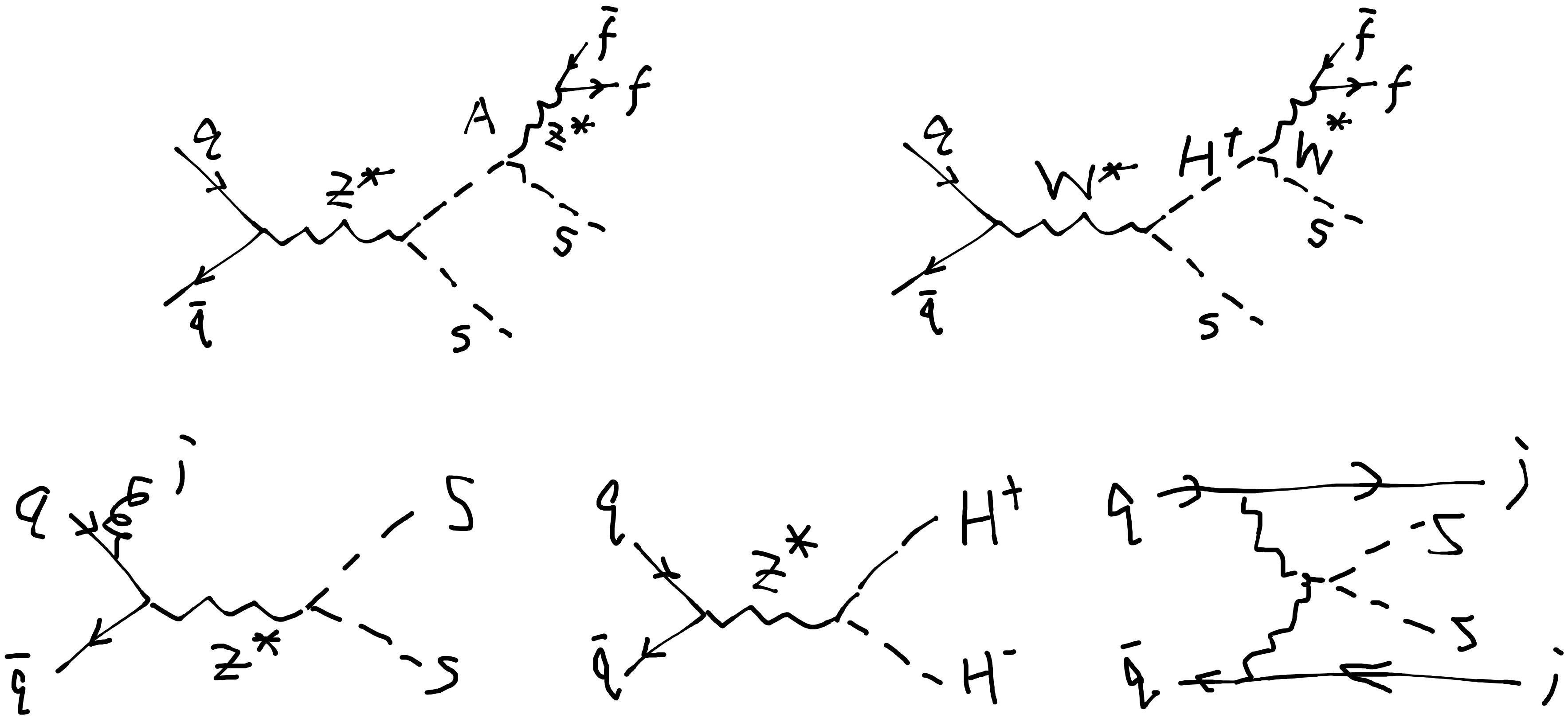
3. Inert 2HDM

LHC signatures:

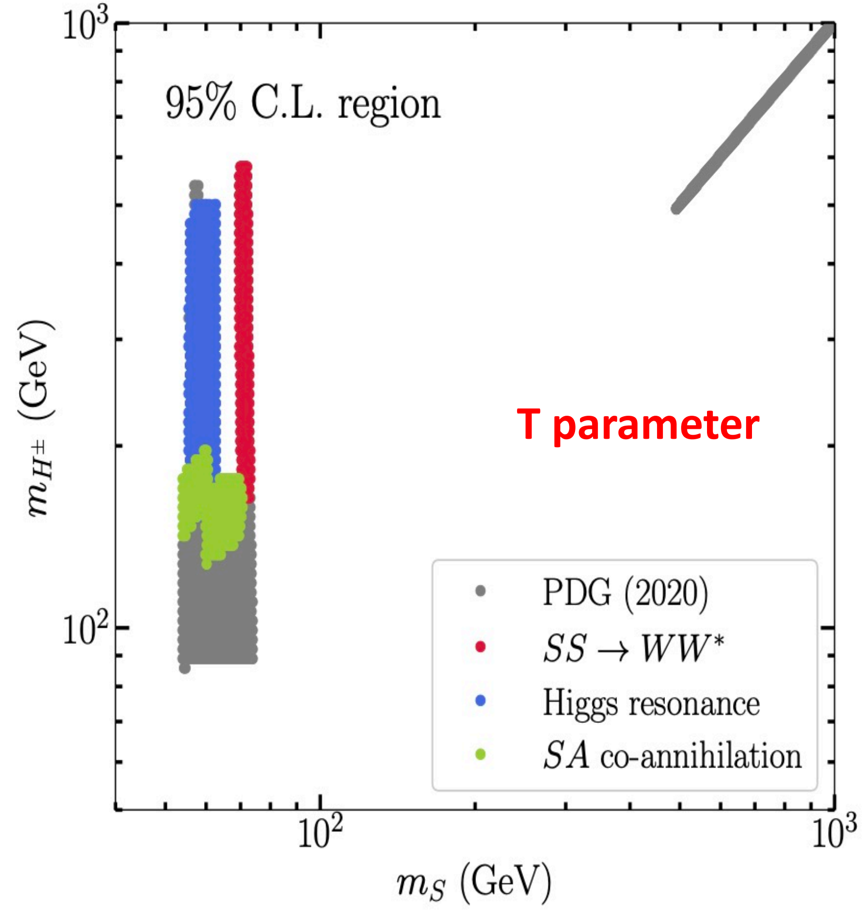
2 leptons+missing E_T

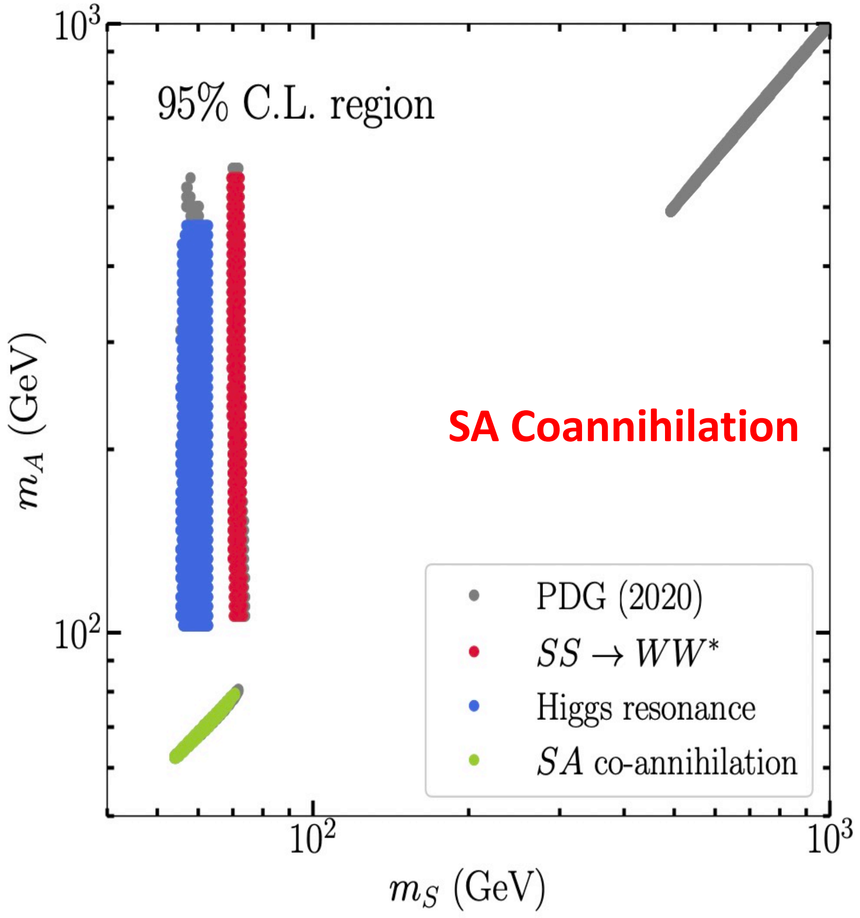
mono-jet

multi-jet+missing E_T



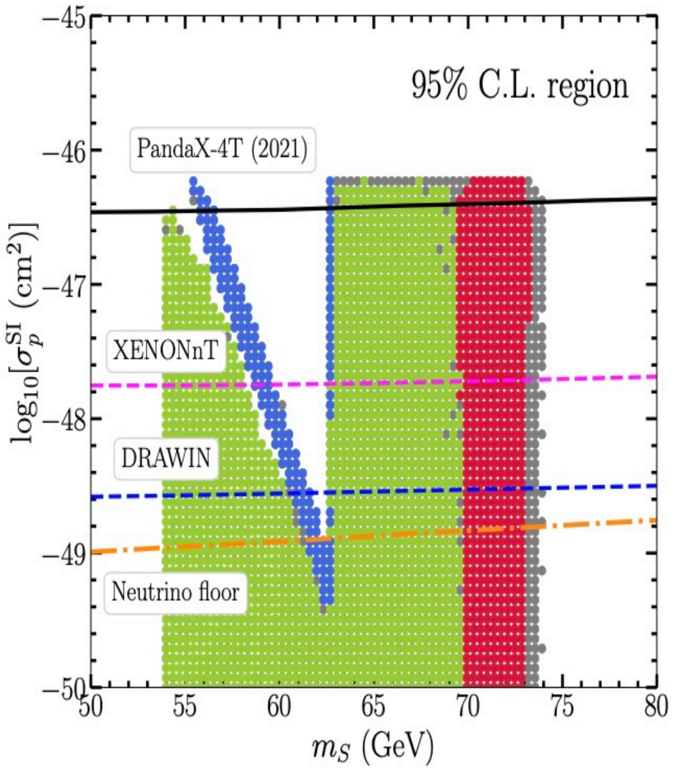
3. Inert 2HDM


95% C.L. region
T parameter
PDG (2020)
$SS \to WW^*$
Higgs resonance
SA co-annihilation
$m_{H^\pm}$ (GeV)
m_S (GeV)
10^2
10^3

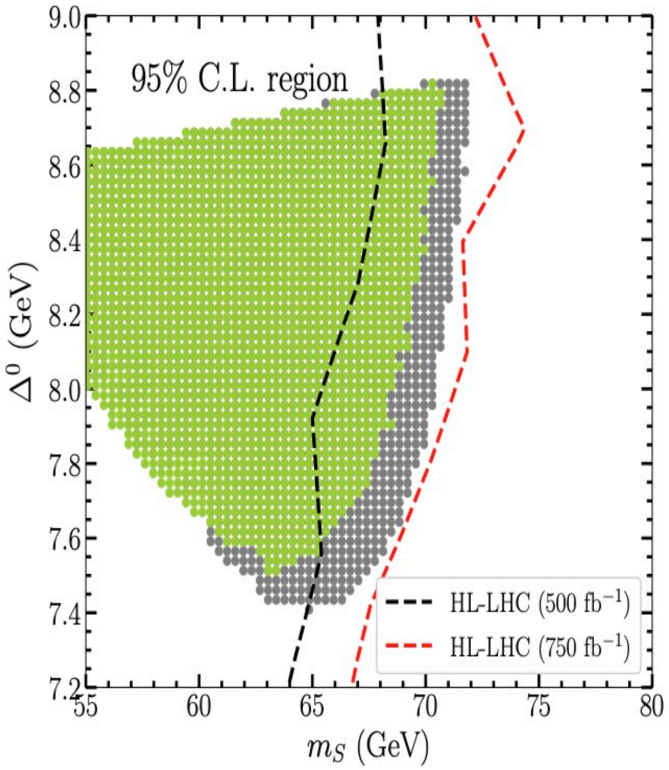

95% C.L. region
SA Coannihilation
PDG (2020)
$SS \to WW^*$
Higgs resonance
SA co-annihilation
m_A (GeV)
m_S (GeV)
10^2
10^3

3. Inert 2HDM

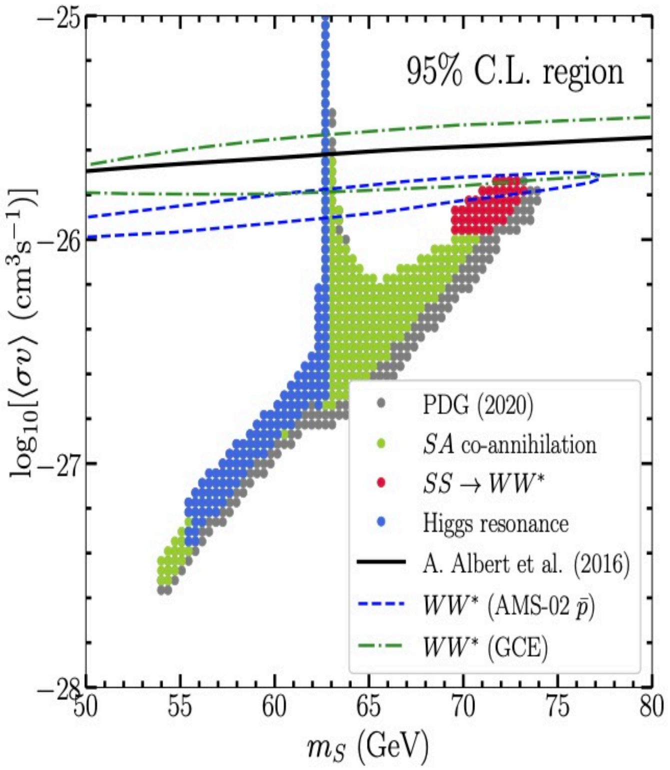
Direct Detection



LHC

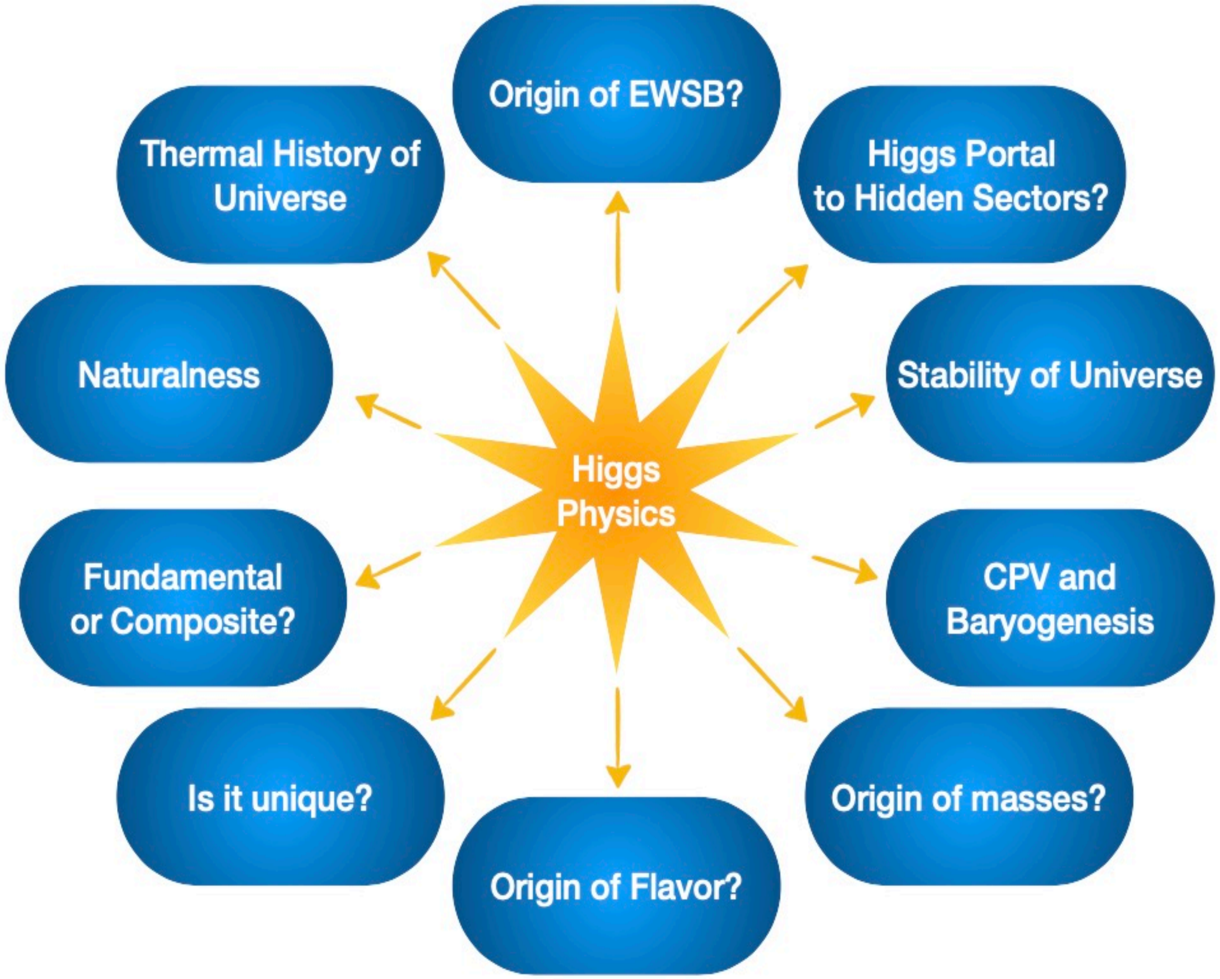


Indirect Detection



It is very predictive, and can be tested soon!

4. Summary



Thank you!